

MoDOT

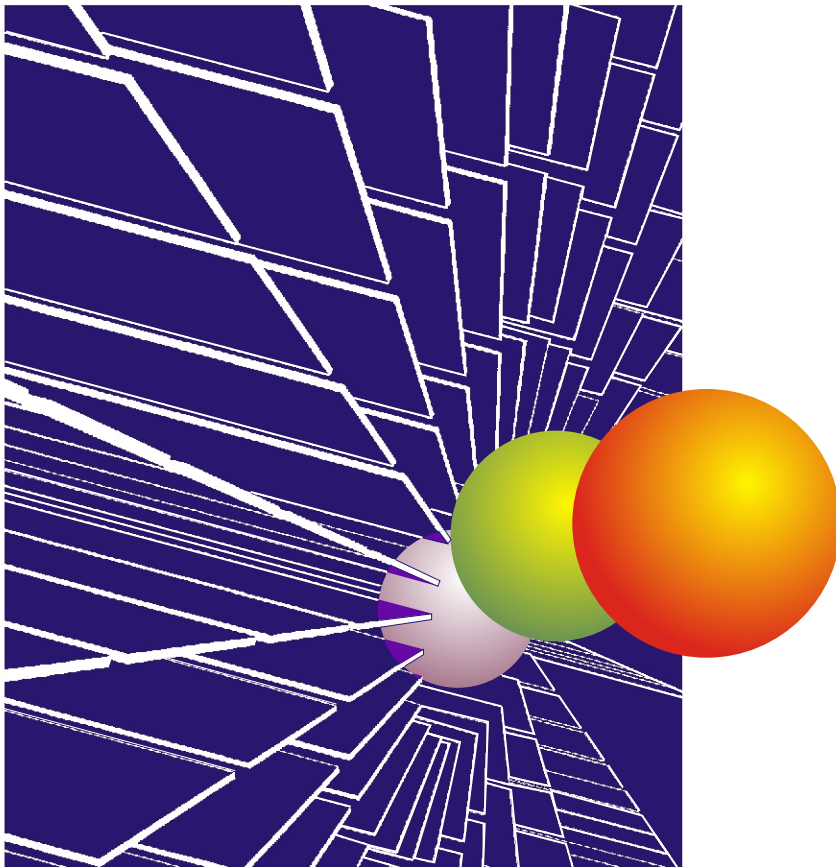
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Assessment of Multiple Left-Turn Phasing Strategies

MISSOURI DEPARTMENT OF TRANSPORTATION
RESEARCH, DEVELOPMENT AND TECHNOLOGY

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16. Abstract <p>Left-turn movements at an intersection affect the capacity of that intersection. As the left-turning volume at an intersection continues to grow, the green time required to meet the left-turn demand increases. This, in turn results in longer cycle lengths. Also with the increase in the left-turn volume, the queues lengthen resulting in greater storage length requirements. The combinations of these effects tend to increase delay at the intersection and lower the level of service. Installation of multiple left-turn lanes (dual and triple) can result in the reduction of vehicle queue lengths, delays and left-turn storage length.</p> <p>In Missouri, multiple left-turns are gaining popularity. However, the installation of these multiple left-turn raises questions for which the Missouri Department of Transportation (MoDOT) has not yet developed answers. Specifically, MoDOT seeks guidance on</p> <ul style="list-style-type: none"> • Criteria for determining when to install double and triple left-turns; • The type of phasing to be used for dual and triple left-turn lanes; • Whether to use “Dallas” or permitted lead-lag phasing for any left-turn lanes; • Where to begin reducing the number receiving lanes downstream of an intersection with multiple left-turn lanes. <p>Based on the current practices being followed by various state DOTs and from the review of literature the following recommendations are being made.</p> <ul style="list-style-type: none"> • Capacity analysis should be used to determine the set of conditions for upgrading left-turn lanes from single to dual and dual to triple. • If it is not feasible to perform capacity analysis due to a lack of resources, the following rules of thumb may be used for determining the point of upgrade: <ul style="list-style-type: none"> ▪ When left-turning volume ≥ 300 vph, upgrade from single to dual left-turn lane. ▪ When left-turning volume ≥ 600 vph, upgrade from dual to triple left-turn lane. • Protected only phasing should be used for dual and triple left-turn lanes. • “Dallas” phasing should be used instead of lead-lag protected + permissive phasing for single left-turn lanes along with R10-12a (combined R10-10L and R10-12) sign to avoid confusion to the adjacent through traffic. • For downstream lane drop distance, consider the solution by Shen as shown in Table 2. 			
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EXECUTIVE SUMMARY

With congestion increasing on Missouri's roads, the need for mitigating strategies has become more critical. One of these strategies that has a potential in Missouri is to add multiple left-turn lanes at signalized intersections.

Installation of multiple left-turn lanes reduces the required left-turn green time, queue lengths and the intersection delay. As multiple left-turn lanes have these advantages, it is important to determine the criteria when to upgrade the left-turn lanes.

However, the installation of these multiple left-turn raises questions for which the Missouri Department of Transportation (MoDOT) has not yet developed answers. Specifically, MoDOT seeks guidance on

- Criteria for determining when to install double and triple left-turns;
- The type of phasing to be used for dual and triple left-turn lanes;
- Whether to use "Dallas" or permitted lead-lag phasing for any left-turn lanes;
- Where to begin reducing the number receiving lanes downstream of an intersection with multiple left-turn lanes.

The study methodology consisted of conducting literature review and survey of nineteen state departments of transportation. Based on the findings of the literature review and the survey of state DOTs, we recommend:

- Capacity analysis be used to determine when to upgrade to a dual or triple left turn lane. If capacity analysis proves infeasible then upgrade the single left-turn to dual and dual to triple when the left-turning volumes exceed 300 vph and 600 vph respectively.

- Protected only phasing should be used for multiple left-turn lanes as it provides more safety to left-turners compared to other types of phasing.
- “Dallas” phasing can be used for single left-turn lanes instead of lead-lag protected + permissive phasing but care should be taken to avoid any confusion to the adjacent through traffic by providing additional signage.
- Determine the distance at which to begin dropping a receiving lane using Table 2 of this report.

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1 INTRODUCTION

Left-turn movements at an intersection affect the capacity of that intersection. As the left-turning volume at an intersection continues to grow, the green time required to meet the left-turn demand increases. This, in turn results in longer cycle lengths. Also with the increase in the left-turn volume, the queues lengthen resulting in greater storage length requirements. The combinations of these effects tend to increase delay at the intersection and lower the level of service. Installation of multiple left-turn lanes (dual and triple) can result in the reduction of vehicle queue lengths, delays and left-turn storage length.

Dual and triple left-turn lanes require less green time compared to single left-turn lanes to meet the left-turning vehicle demand. This saving in the green time can be allocated to the other operations at the intersection thus resulting in the increase of intersection capacity. “Left-turn movement capacity can be increased by an average of 80% during peak hours when a dual left-turn lane is installed on a high volume left-turn approach” (1). The installation of triple left-turn lanes result in similar advantages like increase in the intersection capacity, reduction in the minimum green time given to the left-turn movement so that it can be assigned to other intersection movements (2).

In Missouri, multiple left-turns are gaining popularity. However, the installation of these multiple left-turn raises questions for which the Missouri Department of Transportation (MoDOT) has not yet developed answers. Specifically, MoDOT seeks guidance on

- Criteria for determining when to install double and triple left-turns;
- The type of phasing to be used for dual and triple left-turn lanes;
- Whether to use “Dallas” or permitted lead-lag phasing for any left-turn lanes;

- Where to begin reducing the number receiving lanes downstream of an intersection with multiple left-turn lanes.

This study uses a combination of literature review and a nationwide survey of state practice to provide answers to these questions.

2 OBJECTIVES

The objectives of this study are to determine:

- The criteria for upgrading left-turn lanes to dual or triple lanes;
- The type of phasing to be used with dual and triple left-turn lanes;
- Whether to use “Dallas” or permitted lead-lag phasing for any type of left-turn lane;
- At what distance downstream of an intersection with dual or triple left-turn lanes to drop a receiving lane.

3 PRESENT CONDITIONS

3.1 UPGRADING LEFT-TURN LANES

3.1.1 Single to Dual Left-Turn Lanes

Section 4-05.3 (3) (a) of MoDOT PDM states “when the peak left-turning traffic exceeds 300 vph, provision for two-lane left turns is considered.”

3.1.2 Dual to Triple Left-Turn Lanes

The project development manual does not give any guidelines for upgrading dual left-turn lanes to triple.

3.2 PHASING FOR MULTIPLE LEFT-TURN LANES

MoDOT uses protected only phasing for dual left-turn lanes and there are no written guidelines for phasing triple left-turn lanes.

3.3 “DALLAS” PHASING

The project development manual does not give any guidelines for the use of “Dallas” phasing for any left-turn lanes.

3.4 DOWNSTREAM LANE DROP FOR MULTIPLE LEFT-TURN LANES

The project development manual does not give any guidelines for determining the distance at which to drop the receiving lanes downstream of an intersection with multiple left-turn lanes.

4 TECHNICAL APPROACH

In order to develop guidelines for the project objectives, a two step process was followed by the research team. In the first step, a review of literature was conducted. In the second step, an email survey was conducted to find the current practices followed by different state DOTs. The following sections describe the methodology in detail.

4.1 LITERATURE REVIEW

4.1.1 Upgrading Left-Turn Lanes

To avoid the disadvantages such as increased delays, queue lengths etc., caused by the increase in the left-turning volume, left-turn lanes can be upgraded from single to dual or from dual to triple. The use of a dual left-turn lane configuration also increases the overall capacity of an intersection by reducing the required left-turn green time (4). By increasing the capacity, more left-turning vehicles are allowed to traverse the intersection within a given length of green time. This results in the reduction of average vehicle delay. One of the aims of this research was to determine the set of conditions, at which to upgrade left-turn lanes from single to dual and dual to triple. The review of literature did not reveal any specific guidelines for upgrading left-turn lanes. However, some of the studies suggest rules of thumb for upgrading left-turn lanes.

4.1.2 Phasing for Multiple Left-Turn Lanes

Signal phasing is very important for the successful functioning of multiple left-turn lanes. Three types of phasing can be used for left-turns: permissive only, protected (exclusive) only and protected (exclusive) + permissive phasing. According to Upchurch (5), protected only phasing provides more safety with larger delay and permissive only phasing provides less safety with least amount of delay. Protected + permissive phasing lies in between protected only and permissive only phasing in terms of safety and delay. It should be noted that the above ranking

is for single left-turn lanes. In the case of multiple left-turn lanes, any combination of permissive phasing decreases delay while increasing the risk of accidents. Therefore, choosing a phasing type for multiple left-turn lanes involves a tradeoff between safety and delay.

4.1.3 “Dallas” Phasing

“Dallas” phasing is also known as permitted lead-lag (PLL) phasing (see Figure 1). This phasing was developed in 1978, in Dallas, Texas and hence the name “Dallas” phasing. This phasing is used to eliminate the left-turn trap, which is also known as yellow trap that occurs in lead-lag protected + permitted phasing. “Dallas” phasing eliminates the left-turn trap by introducing a permissive green for left-turning vehicles during the opposite left-turning vehicles protected phase.

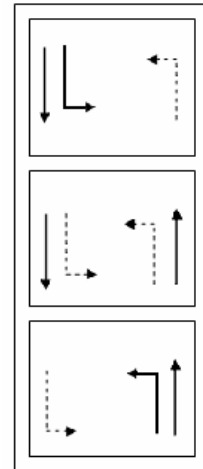


Figure 1: “Dallas” Phasing

4.1.4 Reducing Number of Downstream Receiving Lanes

At an intersection with triple left-turn lanes, three vehicles will be simultaneously making left-turns. To receive these vehicles the number of receiving lanes on the downstream roadway should be same as the number of left-turning lanes. Sometimes, at an intersection with triple left-turn lanes, the number of receiving lanes on the downstream may only be two instead of three. In such a situation, “a triple left-turn may be installed by including a transitioning three-lane section on the two-lane facility, creating essentially a merging section with a lane-drop condition some place downstream” (6). Also at some intersections, due to geometric or space restrictions it is not possible to carry all the three left-turning lanes up to the next intersection or it may not be economical to carry all the lanes up to next intersection. Under such conditions, one of the

receiving lanes is dropped after continuing it to some distance downstream of the intersection. This distance measured from the beginning of the departing approach to the beginning of the lane-drop location, excluding the lane-drop taper section, is known as Merging Section Length.

This merging section length should be sufficiently long enough to avoid any delay to the left-turning vehicles and through vehicles on the approach. “When the merging section length is not sufficiently long, vehicles traveling on the lane being dropped will be forced to slow down, stop, or perform unsafe maneuvers, resulting in undesirable traffic operations and safety problems” (6) and can cause queues to overflow into the intersection. To avoid this traffic disruption, it would be useful to know the minimum merging length needed.

4.2 SURVEY OF STATE DOTs

To obtain the information on current state of practice for phasing left-turns with multiple lanes, a questionnaire was sent to all the states Departments of Transportation (DOTs) by Missouri Department of Transportation (MoDOT) officials via an e-mail.

The questionnaire contained the following questions:

1. Does your agency currently have any criteria for upgrading left-turns to dual or triple left-turn lanes? If yes, please send us a copy of the criteria.
2. Under what conditions does your agency allow permissive phasing at dual and triple left-turn lanes?
3. Under what conditions does your agency allow protected + permitted phasing for dual and triple left-turn lanes?
4. Under what conditions does your agency allow “Dallas” phasing for any left-turn lanes?
5. At what distance downstream of an intersection with dual or triple left-turn lanes does your agency allow a reduction in the number of receiving lanes?

Nineteen states sent in their responses to the above questions (see fig. 2). The following section gives the summary of the states DOTs replies for the questions asked. The detailed replies can be seen in the Appendix B.

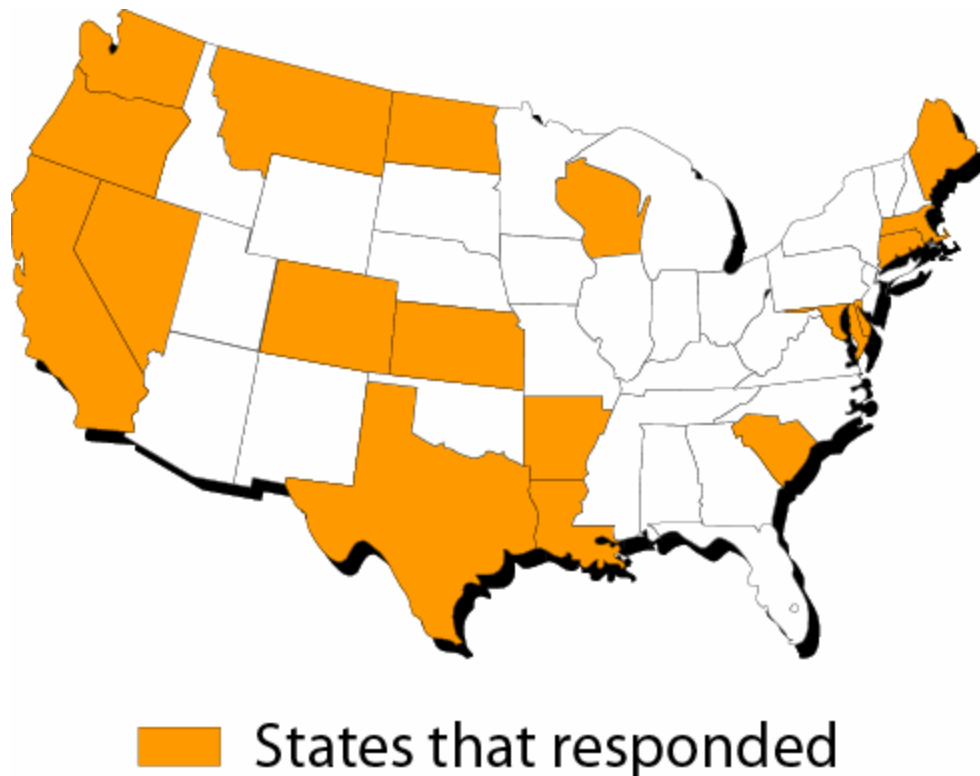


Figure 2 : United States Map Indicating the States that Responded to the Survey

4.2.1 Upgrading Left-Turns to Dual or Triple Left-Turn Lanes

Most of the states that responded to the survey replied that they do not have any written criteria for upgrading left-turns to dual or triple left-turn lanes. Some of the states use capacity analysis (Arkansas, Kansas, Louisiana, Maine, North Dakota, and Maryland). Texas uses TxDOT Design Division's Highway Design Manual (7) which states "For major signalized intersections where high peak hour left-turn volumes are expected, dual left-turn lanes should be considered". Some states follow the rule of thumb of left-turning volumes over 300 vph (Nevada, South Carolina, California), while others follow left-turning volumes over 400 vph (Arkansas, Kansas) and left-

turning volumes over 250-300 vph (Wisconsin) for upgrading single left-turn lane to dual left-turn lane.

Most of the states that responded do not have triple left-turn lanes. Only Nevada replied to the question of when they would upgrade dual left-turn lane to triple left-turn lane. Nevada uses a rule of thumb of left-turning volumes over 600 vph to upgrade dual left-turn lane to triple left-turn lane.

4.2.2 Permissive Phasing at Dual and Triple Left-Turn Lanes

Of all the states surveyed only Montana uses permissive phasing. In Montana, permissive phasing is currently used at only one location and on only one approach because there is no left-turning traffic on the opposite approach. They are continuing with permissive phasing, only because there were no accidents recorded and no public complaints about permissive phasing.

4.2.3 Protected + Permitted Phasing at Dual and Triple Left-Turn Lanes

Only two states, Colorado and Maryland use protected + permissive phasing at dual left-turn lanes. Colorado uses both protected + permissive and protected (exclusive) phasing for dual left-turns and Maryland uses protected + permissive phasing when there is lack of left-turn storage length.

4.2.4 “Dallas” Phasing for any Left-Turn Lanes

Most of the states that responded to the survey replied that they were not familiar with “Dallas” Phasing. Arkansas provides “Dallas” phasing only when they have to use lead-lag phasing. Nevada allows “Dallas” phasing on case-by-case basis and if it creates any problem, they discontinue it. Texas DOT does not operate any signal using “Dallas” phasing but several municipalities in Texas utilize it.

4.2.5 Downstream Lane Reduction

Three states namely Montana, Rhode Island, Wisconsin do not allow a reduction in number of receiving lanes downstream of the intersection with dual or triple left-turn lanes. Arkansas considers capacity analysis and geometric constraints whereas Delaware considers only geometric constraints for calculating the distance at which the number of receiving lanes are to be reduced. Iowa and Kansas do not have any written guidelines for the distance of reducing the number of receiving lanes but Kansas uses ITE's guidelines for Urban Major Street Design Book. Maryland uses $(\text{reduction width} \times \text{speed})/2$ and Maine uses $(12 \times \text{green})$ for calculating the distance required for reducing the number of receiving lanes. North Dakota uses AASTHO and HCM (8) guidelines and Nevada uses MUTCD (9) and AASTHO Green Book (10) guidelines. The research team reviewed AASTHO Green Book and MUTCD to find the guidelines for lane drop distance. However it was found that AASTHO Green Book and MUTCD give guidelines for calculating taper lengths at lane drop and the distance of advance lane drop warning sign but not the lane drop distance. Oregon uses a SYNCHRO model, which considers volume, speed and proximity of other intersections. Texas DOT's decision is based on engineering judgment and TxMUTCD requirements. South Carolina drops the receiving lane at 1000 ft downstream of the intersection. Washington drops the number of receiving lanes at a distance which is based on the posted speed. If the posted speed is 45 mph or higher, the minimum length to be used is 1500 ft. If the posted speed is less than 45 mph, the minimum length should be sufficient so that the advance lane reduction warning sign will be placed not less than 100 ft beyond the intersection area. Louisiana decides the distance required for dropping the downstream receiving lane depending on driver destination, traffic distribution within the turning lanes and/or through lanes and the site condition.

Connecticut uses the following equation and table in addition to engineering judgment and green time for calculating the distance downstream of an intersection at which a receiving lane can be dropped:

The taper length (L) is calculated from

$$L = \begin{cases} 0.6WS & \text{if } S \geq 70 \\ \frac{WS^2}{155} & \text{if } S \leq 60 \end{cases}$$

Where L = taper length, m

W = 3.6 m

S = design speed, kmph

Table 1: Downstream Lane Drop Distances Followed by State of Connecticut

Design Speed (Km/h)	D_E (m)	Taper , L(m)
50	90	60
60	90	90
70	110	150
80	160	170
90	240	190
100	330	220
110	460	240

(Values rounded)

D_E is that distance required by the vehicle to accelerate from a stop to 10 kmph below the design speed (90 m minimum).

5 RESULTS AND DISCUSSION

5.1 UPGRADING LEFT-TURN LANES

5.1.1 Upgrading from Single to Dual Left-Turn Lanes

Many studies from the literature reveal that the single left-turn lane is upgraded to dual when the left-turning volume exceeds 300 vph. These studies include

- Chapter 10 of Highway Capacity Manual 2000 (8), Table 10-13, mentions that double exclusive left-turn lanes should be provided when the left-turning volume is greater than or equal to 300 vph.
- As per section 4-05.3 (3) (a) of MoDOT PDM (3), “when the peak left-turning traffic exceeds 300 vph, provision for two-lane left turns is considered”.
- A study by ITE Technical Council Committees 5P-5 and 5S-1 says that, “when design volumes indicate a left-turning traffic of at least 300 vph then the use of exclusive dual left-turn lanes may be considered” (11).
- A Transportation Research Board (TRB) Report 279 says, “As a rule, dual left-turn lanes are considered in locations with left-turn demands of 300 vph or more” (12).
- A study by technical committee 4L-M of Institute of Transportation Engineers (ITE), Traffic Engineering Journal revealed that “The California Dept. of Transportation reports that a double left-turn lane will be considered warranted when peak-hour left-turn approach volumes exceed 300 vehicles and the city of San Diego, California reports its consideration of double left-turn lanes when peak hour left-turn approach volumes exceed 200 vehicles” (13).

In the survey, most of the states replied that they do not have any written criteria for upgrading left-turns to dual. The criteria followed by the remaining states can be classified into three categories. They are:

- Capacity Analysis: Some of the states like Louisiana, Maine, Maryland and North Dakota use capacity analysis for determining when to upgrade single left-turn lanes to dual left-turn lanes.
- Rule of Thumb: California, Nevada, and South Carolina follow the rule of thumb of left-turning volumes over 300 vph, while Wisconsin upgrades the single left-turn lane to dual when the left-turning volume exceeds 250-300 vph.
- Both Capacity Analysis and Rule of Thumb: Arkansas and Kansas use both the capacity analysis and the rule of thumb of 400 vph for determining the set of conditions, at which to upgrade the single left-turn lane to dual.

5.1.2 Upgrading from Dual to Triple Left-Turn Lanes

Triple left-turn lanes are rare as compared to dual. Therefore, not much work has been done in the past to find the criteria when to upgrade dual left-turn lane to triple. A study done by Ackeret (14) reveals that a triple left-turn should be installed when the left-turning volume exceeds 600 vph.

In the survey, regarding the triple left-turn lanes, most of the states responded that they do not have triple left-turn lanes. Nevada was the only state that replied to the question of upgrading the dual left-turn lanes to triple. They use a left-turning volume over 600 vph as their rule of thumb to upgrade dual left-turn lane to triple left-turn lane.

Summary of Upgrading Left- Turn Lanes

The survey of state DOTs revealed that approximately 30% of the states use capacity analysis for determining the set of conditions at which to upgrade the left-turn lanes from single to dual. So capacity analysis should be used to determine the set of conditions for upgrading left-turn lanes from single to dual and dual to triple. If it is not feasible to perform capacity analysis due to a lack of resources, the following rules of thumb may be used for determining the point of upgrade:

- When left-turning volume is greater than or equal to 300 vph, upgrade single left-turn lane to dual.
- When left-turning volume is greater than or equal to 600 vph, upgrade dual left-turn lane to triple.

5.2 PHASING FOR MULTIPLE LEFT-TURN LANES

Although different types of phasing are used for left-turn lanes, most of the literature suggests that protected only phasing should be used for dual and triple left-turn lanes as it provides more safety to left-turners compared to the other types of phasing (*1, 15, 16, 17, 18*).

- A study done by Traffic Signal Technical Committee of Colorado/Wyoming Section of Institute of Transportation Engineers (ITE) (*19*) found that the accident rates for dual left-turn lanes with permissive only phasing are higher compared to dual left-turn lanes with protected only phasing however the protected phasing resulted in higher delay compared to protected + permissive phasing.
- Another study done by Tarrall et al (*4*) found that the dual left-turn lanes with protected + permissive phasing have more conflict points than dual left-turn lanes with protected only phasing.

- Stamatiadis and Agent state that, “Any type of permitted left-turn phasing is not appropriate when two exclusive left-turns are used. Use of protected only phasing should be considered if the left-turn volume routinely exceeds 300 vph” (20).
- Ackeret states that, “As the triple left-turn lane operation deals with high volumes of vehicles, the left-turn movement should be a fully protected signal phase” (14).

In the survey, most of the states replied that they do not allow any type of permissive phasing for the multiple left-turn lanes because of associated risk. Montana allows permissive phasing at one multiple left-turn approach. In the survey, Montana replied, “Our agency does not introduce permissive signal phasing into the operation of dual or triple left-turn lanes. We only allow it at one location in the state to operate permissive and on only one approach. There are no left-turns on the opposite approach. It was not a decision made by existing staff and is only being allowed to continue permissive because its circumstances have not recorded any accident trend or public complaint”. Colorado and Maryland use protected + permissive phasing at dual left-turn lanes. Maryland uses protected + permissive phasing when there is lack of left-turn storage length.

Summary of Phasing

The vast majority of the responding states use protected only phasing for multiple left-turn lanes. This is also in consensus with the findings of literature review.

5.3 “DALLAS” PHASING

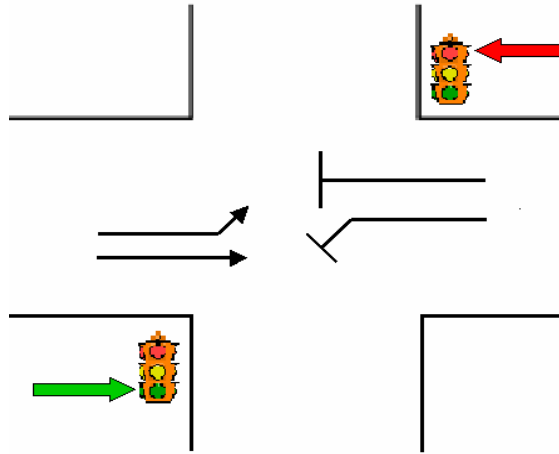
Left-turn trap occurs when the lead-lag phasing is overlapped with protected + permissive phasing. This problem of left-turn trap can be eliminated by using “Dallas” phasing. The following section explains how the left-turn trap occurs in lead-lag protected + permitted phasing.

With reference to figure 3 in the next page,

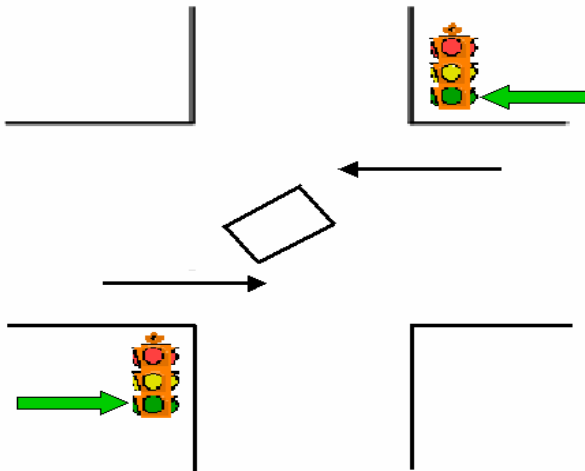
In Phase I, the leading eastbound left-turner has a protected phase and the adjacent through traffic has a green signal, while the lagging westbound left-turning and through traffic have a red signal.

In phase II, the east and west bound through traffic have a green signal and both the left-turners have a permissive phase. Left-turners make a turn only when there is an acceptable gap between the through traffic. During this phase, the left-turner moves into position and waits for an acceptable gap in the opposing through traffic.

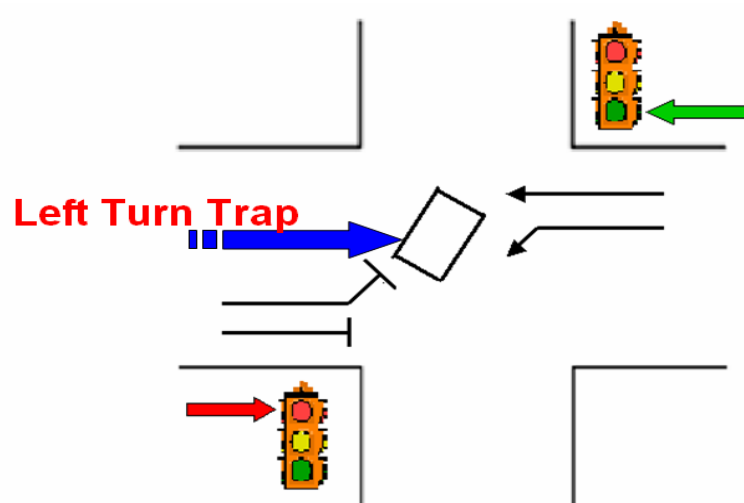
In phase III, the lagging westbound left-turn has a protected phase and the adjacent through traffic has a green signal while the east bound left and through traffic have a red signal. During this phase, the eastbound left-turner who is waiting for a gap in the opposing through traffic, incorrectly assumes that as the adjacent through traffic has a red signal the opposing through traffic will also have a red signal. Assuming so, the left-turner tries to sneak through the intersection, which results in a left-turn trap as shown in the figure.



Phase I - Leading protected left-turn phase



Phase II – permissive left-turn phase



Phase III-Lagging protected left-turn phase

Figure 3: Left-Turn Trap

After comparing figures 4 and 5, it can be seen that “Dallas” phasing introduces an additional permissive phase, which helps in eliminating the left-turn trap.

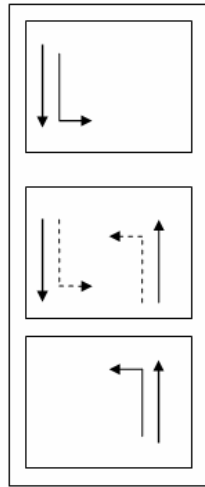


Figure 4: Leading-Lagging Protected + Permissive Phasing

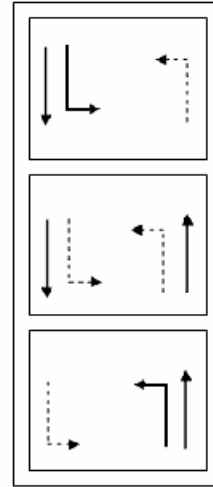


Figure 5: “Dallas” Phasing

A study was done by Ousama Shebeeb (21) to compare “Dallas” phasing with other types of phasing for left-turns with respect to delay and safety. The other phasing types compared in the study include permissive only, protected only, and protected + permissive phasing. This study was based on the data collected from 54 intersections (179 approaches) in Texas and Louisiana. In terms of delay, the study concluded that permissive only phasing resulted in least amount of delay followed by “Dallas” phasing and protected + permissive phasing while protected only phasing resulted in maximum amount of delay. Whereas, protected only phasing was found to be the safest type of phasing followed by “Dallas” phasing and protected + permissive phasing. Permissive only phasing was found to provide least safety to the left-turners.

“Dallas” phasing is a complex type of phasing. In order to avoid any confusion that may be caused to inner through lane traffic, R10-12a sign (see fig. 6), which is combination of R10-10L and R10-12 should be provided (22). Louvers should be used to shield the left-turn display so that the left-turn green signal cannot be seen by the adjacent through vehicles.



Figure 6: R10-12a Sign

In the survey, most of the states replied that they are not familiar with “Dallas” phasing. Only Arkansas, Nevada and several municipalities in Texas utilize “Dallas” phasing.

Summary of “Dallas” Phasing

“Dallas” phasing can be used for single left-turn lanes with the provision of R10-12a sign that is shown in figure 6.

5.4 REDUCING NUMBER OF DOWNSTREAM RECEIVING LANES

A study was conducted by Shen (6) to calculate the minimum merging section length for triple left-turn lanes with downstream lane reductions. As there were not many triple left-turn lanes with downstream lane drops, she used CORSIM simulation to model the lane drop condition. Shen modeled the average delay experienced by the left-turning vehicles traveling on the downstream roadway as a function of merging section length, left-turn green time, percentage of heavy vehicles and design free flow speed of downstream roadway. This model was formulated by conducting simulation runs, plotting graphs and finally through the curve fitting. The minimum merging section lengths given by Shen for various combinations of left-turn green time, percentage of heavy vehicles in left-turning traffic and design free flow speed of downstream roadway are given Table 2. It should be noted that these values given by Shen for

triple left-turn lanes can also be used for dual left-turn lanes, as there are no considerable differences in the operational characteristics of dropping from three to two or two to one lanes.

Table 2: Minimum Downstream Lane Drop Distance Provided by Qiong "Joan" Shen

Green Time (s)	Percent of Heavy Vehicles						
	0%	5%	10%	15%	20%	25%	30%
Downstream free-flow speed = 35 mph							
10	200	212	223	233	242	249	255
20	214	231	246	260	273	284	294
30	228	249	268	286	303	319	333
40	242	268	291	313	334	354	372
50	256	287	314	340	365	388	411
60	270	305	336	366	395	423	450
Downstream free-flow speed = 45 mph							
10	200	215	229	242	254	265	275
20	214	236	256	274	291	305	318
30	228	257	283	306	327	345	362
40	242	278	310	338	364	386	404
50	256	299	337	370	400	426	447
60	270	320	364	403	437	466	490
Downstream free-flow speed = 55 mph							
10	205	220	234	247	259	270	280
20	220	243	264	282	299	314	328
30	235	267	294	318	338	358	376
40	250	290	323	350	378	402	424
50	266	313	353	388	418	446	472
60	280	335	382	422	457	490	520

Source: (6)

Sando (23) raised several concerns about the ability of CORSIM to model multiple left-turns. Specifically, the concerns were:

- CORSIM does not recognize the unique problems of trucks having to make turns simultaneously in adjacent lanes.
- CORSIM does not show any difference in capacities as the intersection angle is changed from obtuse to acute.
- CORSIM gives no difference in capacities for different lane widths.

While the research team understands the nature of these concerns, the Shen study deals with delays to vehicles from the merge behavior rather than the delay due to the change in intersection capacity with change in the intersection angle. It is also rare that trucks will simultaneously make left-turns from adjacent lanes. Therefore the above inabilities of the CORSIM do not have significant affect on the merging section length calculations.

In the survey, Montana, Rhode Island, Wisconsin replied that they do not allow a reduction in number of receiving lanes on the downstream of the intersection with dual or triple left-turn lanes. Iowa and Kansas do not have any written guidelines for the distance of reducing the number of receiving lanes. Louisiana decides the distance required for dropping the downstream receiving lane depending on driver destination, traffic distribution within the turning lanes and/or through lanes and the site condition. Texas DOT's decision is based on engineering judgment and TxMUTCD requirements. Kansas uses ITE's guidelines for Urban Major Street Design Book. The criteria used by the remainder of states that responded can be classified into the following six categories.

- Geometric Constraints: Delaware considers geometric constraints whereas Arkansas considers geometric constraints and capacity analysis for calculating the distance at which the number of receiving lanes are to be dropped.
- AASHTO Guidelines: Nevada uses AASTHO Green Book (10) along with MUTCD (9) guidelines and North Dakota replied that they use AASHTO and HCM (8) guidelines.
- Empirical Formulae: Some states like Maryland and Maine use empirical formulae for determining the downstream lane drop distance. Maryland uses a formula of $(\text{reduction width} \times \text{speed})/2$ and Maine uses $(12 \times \text{green})$.

- Rule of Thumb: South Carolina uses a rule of thumb of 1000 ft for dropping the downstream receiving lane. Washington drops the number of receiving lanes at a distance, which is based on the posted speed. If the posted speed is 45 mph or higher, the minimum length is 1500 ft and if the posted speed is less than 45 mph, the minimum length should be sufficient so that the advance lane reduction warning sign will be placed not less than 100 ft beyond the intersection area.
- SYNCHRO Model: Oregon uses a SYNCHRO model, which considers volume, speed and proximity of other intersections.
- Miscellaneous: Connecticut uses the following equation in addition to engineering judgment and green time for calculating the distance downstream of an intersection at which a receiving lane can be dropped:

The taper length (L) is calculated from

$$L = \begin{cases} 0.6WS & \text{if } S \geq 70 \\ \frac{WS^2}{155} & \text{if } S \leq 60 \end{cases}$$

Where L = taper length, m

W = 3.6m; S = design speed, KMPH

The downstream lane drop distances used by Connecticut are given in Table 1.

Summary of reducing number of lanes

There is no clear consensus on when to reduce the number of receiving lanes following an intersection. However, the method developed by Shen (6) shows considerable promise.

6 CONCLUSIONS AND RECOMMENDATIONS

Based on the current practices being followed by various state DOTs and from the review of literature the following recommendations are being made.

- **Capacity analysis** should be used to determine the set of conditions for upgrading left-turn lanes from single to dual and dual to triple.
- If it is not feasible to perform capacity analysis due to a lack of resources, the following rules of thumb may be used for determining the point of upgrade:
 - When left-turning volume ≥ 300 vph, upgrade from single to dual left-turn lane.
 - When left-turning volume ≥ 600 vph, upgrade from dual to triple left-turn lane.
- **Protected only** phasing should be used for dual and triple left-turn lanes.
- **“Dallas” phasing** should be used instead of lead-lag protected + permissive phasing for single left-turn lanes along with R10-12a (combined R10-10L and R10-12) sign to avoid confusion to the adjacent through traffic.
- For downstream lane drop distance, consider the solution by **Qiong “Joan” Shen** as shown in Table 2.

7 IMPLEMENTATION PLAN

The recommendations made in this report need to be reviewed by MoDOT via its internal processes. If approved, these recommendations need to be incorporated into the Project Development Manual. Finally, to increase and promulgate these findings within the districts, we recommend that the researchers present these findings at the Transportation Engineers Association Meeting.

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APPENDIX A

Work Plan

Work Plan

Date: July 1, 2002

Project Number: RI02-014

Title: Assessment of Multi-lane Left-turn Phasing Strategies

Research Agency: Curators of the University of Missouri
University of Missouri-Rolla

9 PRINCIPAL INVESTIGATORS:

Dr Mohammad Qureshi, Assistant Professor, PI
Dr. Gary Spring, Associate Professor, Co-PI

10 OBJECTIVE:

To examine the state of practice for phasing left-turns with multiple lanes, compare and contrast alternative strategies and to develop a set of guidelines that may be used by MoDOT traffic engineers in designing traffic signalization schemes for left-turns with multiple lanes.

11 BACKGROUND:

With the need for more efficient use of existing traffic facilities comes the need to move greater numbers of vehicles safely through left turns in the shortest possible time. There exist several left-turn phasing strategies meant to accomplish this. The Highway Capacity Manual however provides little guidance with respect to phasing choice and provides no methodology for phasing of multiple left-turn lanes. As volumes increase left-turn phasing becomes ever more critical in addressing congestion and safety problems.

There are no national guidelines for multiple left-turn signal phasing design. MoDOT policy says dual left-turns should be protected phasing, but the policy does not mention triple left-turns. MoDOT Traffic Business Unit has received several requests for triple left-turns design, primarily from St. Louis area. So it is practical to have a guideline for triple left-turn phasing design, and MoDOT Traffic Business Unit also has the intention to use triple left-turn design as a planning and modifying tool. Therefore, a left-turn phasing guideline is a key asset for MoDOT.

12 ACTION PLAN:

1. Assess state of practice

- 1.1. Review literature on left-turn phasing strategies for dual and triple left turn lanes. The focus of the review will be to identify potential benefits and range of application for these strategies.
- 1.2. Survey a select set of states to determine if they have any policy on left-turn phasing and what that policy is. The states will be chosen in consultation with MoDOT.
2. Develop a table of benefits and range of applications for strategies identified in task 1.
3. Demonstrate impacts of possible strategies
 - 3.1. Identify existing dual and triple left-turn intersections
 - 3.2. Collect traffic data for intersections in 3.1
 - 3.3. Develop Synchro models for intersections in task 3.1.
 - 3.4. Apply alternative strategies to identify impacts on queuing and delay.
4. Recommend draft guidelines on phasing for dual and triple left-turn intersections.
5. Prepare final report summarizing findings and recommendations.
6. Present the findings and recommendations to MoDOT staff

Method of Implementation:

The draft guidelines prepared as part of this research are expected be incorporated into MoDOT policy after proper review.

Anticipated Benefits:

This research will assist MoDOT in optimizing signal timing resulting in reductions in delays.

Research Period: August 1, 2002 – December 31, 2003

Potential Funding: SP & R

Schedule:

	Task 1	Task 2	Task 3	Task 4	Task 5
Aug-02					
Sep-02					
Oct-02					
Nov-02					
Dec-02					
Jan-03					
Feb-03					
Mar-03					
Apr-03					
May-03					
Jun-03					
Jul-03					
Aug-03					
Sep-03					
Oct-03					
Nov-03					
Dec-03					

Staffing:

Dr. Mohammad Qureshi has served as an Assistant Professor in the Civil Engineering Department at the University of Missouri –Rolla since August 2000. He has experience in the areas of traffic impact studies, traffic operations, highway safety, highway-rail crossing policy, data collection procedures, and statistical analysis of transportation data. Dr. Qureshi has published papers on signalized intersection operations and rail-highway grade crossing policy. Dr. Qureshi received his B.S. and M.S. in Civil Engineering from the University of California, Berkeley and his doctorate from the University of Tennessee in August of 2000.

Dr. Gary Spring has more than 25 years of experience in the areas of transportation planning, design, construction, and operations and safety. Prior to joining the faculty at the University of Missouri-Rolla last year, he worked as a professor of civil engineering at North Carolina A&T State University since 1988. Prior to 1988 he worked for 15 years for a state department of transportation, primarily in design, traffic engineering, construction, planning, and research and development. In the last 2 he served at the Project manager level and was involved in environmental impact studies, policy and evaluation questions, and conducted safety related feasibility studies. Dr. Spring has given more than 25 presentations on a variety of safety related topics, expert systems, geographic information systems, systems implementation issues and evaluation methodologies and has published in excess of 30 papers and technical reports on a variety of related topics.

Budget:

<i>Budget Item</i>	<i>Ref.</i>	<i>Total Costs</i>	<i>Requested</i>	<i>CE Match</i>	<i>UMR Match</i>
TOTAL SALARIES	1	\$ 39,010	\$ 37,113	\$ 1,897	
Mohammad Qureshi	1.1	\$ 6,867	\$ 6,867		
Gary Spring	1.2	\$ 1,897		\$ 1,897	
Technician support	1.3	\$ 800	\$ 800		
Graduate Research Assistant	1.4	\$ 29,446	\$ 29,446		
TOTAL FRINGES	2	\$ 2,391	\$ 1,917	\$ 474	
Fringes for Faculty (25% of 1.1+1.2+1.3)		\$ 2,391	1,917	474	
TRAVEL	3	\$ 500	\$ 500		
EQUIPMENT	4	\$ 2,899		\$ 2,899	
SUPPLIES	5	\$ 750	\$ 750		
DIRECT COSTS (1+2+3+4+5)	6	\$ 45,550	\$ 40,280	\$ 5,271	
INDIRECT COSTS (48% of 6-4)	7	\$ 20,473	\$ 16,076	\$ 1,138	\$ 3,258
TOTAL COST (5+6)	8	\$ 66,023	\$ 56,356	\$ 6,409	\$ 3,258

Note: Requested indirect reduced by \$3258 to bring total UMR & CE cost share equal to 24% of direct costs (\$9667)

APPENDIX B

SUMMARY OF THE SURVEY OF STATE DOTs

Table 3: Summary of the Survey of State DOTs for Upgrading the Left-Turn Lanes

State DOT's	<i>Q 1.</i>	Does your agency currently have any criteria for upgrading left-turns to dual or triple left-turn lanes? If yes, please send us a copy of the criteria.
Arkansas	No	No, not written. Decisions are based on capacity analysis. General threshold is 400 vph.
California	Yes	At signalized intersections on multilane conventional highways and on multilane ramp terminals, double left-turn lanes should be considered if the left-turn demand is 300 vehicles per hour or more.
Colorado	No	We do not use any criteria for dual/triple left-turn lanes that are different from National guidelines.
Connecticut	Yes	Our agency does have criteria to consider when designing dual left-turn lanes. The state of Connecticut has never used nor currently plans to use triple left-turn lanes on any state roadways.
Delaware	No	No
Iowa	No	No
Kansas	No	We do not have any written criteria. 400 lefts/hour is the point where we start thinking about it. The need is based upon a capacity analysis, which shows they are needed. There are no triples in the state of Kansas
Louisiana	No	The Louisiana DOT generally incorporates dual and triple left-turn lanes in new construction projects. These are determined by an analysis of the capacity needs.
Maine	No	Our informal policy on dual left-turn lanes is to use them where they are necessary and practical to obtain a reasonable capacity and level of service for the design life of the project. There must be at least two departure lanes away from the intersection, at least for a limited distance. In Maine, we have no triple left-turn lanes and no urban arterials with three thru lanes in each direction. We use LOS, and the HCM
Maryland	Yes	Yes- we use a critical lane volume analysis.
Montana	No	MDT does not have a formal criterion for converting or upgrading left-turns to dual or triple left-turns. Our approach to this issue is base the decisions on an analytical process that involves the intersection capacity/level of service needs and the geometric constraints that are site specific to the intersection.
North Dakota	No	HCM analysis
Nevada	Yes	We use Dual left-turn lanes on volumes over 300 vph and use triple left-turn lanes on volumes over 600 vph.
Oregon	No	ODOT does not have program where we search out locations for multiple turn lanes. We add dual lanes on a case-by-case basis when capacity issues dictate that we need them. We do not have any "triple" left-turn lanes because the lanes are less controllable and we have experienced problems accommodating the mix of large trucks, motor homes and side-by-side car movements. We have experienced seeing motorists migrating from lane to lane.

Table 1 Cont.

State DOT's	<i>Q 1.</i> Does your agency currently have any criteria for upgrading left-turns to dual or triple left-turn lanes? If yes, please send us a copy of the criteria.	
Rhode Island	No	We do not have any criteria for upgrading the dual and triple left-turn lanes. In fact, we do not have any triple left-turn lanes in RI.
South Carolina	No	We do not have a criterion as such. As a rule of thumb, we will investigate a location for dual lefts when the left-turn volume exceeds 300 vph. Based on the studies a recommendation will be made. As to triple lefts, we do not have any in the state.
Texas	Yes	<p>A design criterion is governed by the TX DOT Design Division's Highway Design Manual. The Highway Design Manual provides the following regarding design criteria and dual left-turn lanes. "Urban streets and their auxiliary facilities should be designed for level of service D. The class of urban facility should be carefully selected to provide the appropriate level of service."</p> <p>"Dual left Left-Turn Lanes. For major signalized intersections where high peak hour left-turn volumes are expected, dual left-turn lanes should be considered. As with single left-turn lanes, dual left-turn lanes should desirably include length for deceleration, storage, and taper."</p>
Washington	Yes	<p>Multi left-turn phasing. Multilane left-turns can be effective in reducing signal delay at locations with high left-turning volumes or where the left-turn storage area is limited longitudinally. At locations with closely spaced intersections, a two-lane left-turn storage area might be the only solution to prevent the left-turn volume from backing up into the adjacent intersection. Consider the turning paths of the vehicles when proposing multilane left-turns. At smaller intersections, the opposing left-turn may not be able to turn during the two-lane left-turn phase and it might be necessary to reposition this lane. If the opposing left-turns cannot time together the reduction in delay from the two-lane left-turn phase might be nullified by the requirement for separate opposing left-turn phase. Figure 850-6 shows two examples of two-lane left with opposing single left arrangements.</p> <p>A two-lane exit is required for the two-lane left-turn movements. In addition, this two-lane exit must extend well beyond the intersection. A lane reduction on this exit immediately beyond the intersection will cause delays and backups into the intersection because the left-turning vehicles move in dense platoons and lane changes are difficult. See chapter 910 for the restrictions on lane reductions on intersection exits.</p>
Wisconsin	Yes	<p>Current WisDOT procedure is that multiple left-turn lanes are justified based on an existing or expected capacity problem. No hard & fast traffic volumes are currently used to dictate when to construct a multiple left-turn lane. Rule-of-thumb guidance used is: Dual left-turn should be considered if there are 250-300 vehicles left-turns in the design hour (depending on conflicting thru volumes). I would suspect that the number of designers who use that rule vary substantially state wide. Even if a multiple left-turn is cited as being needed in the future, it may not be constructed immediately. It can be designed for (median width, grading, drainage, location of certain signal or lighting elements, etc) with the intention of constructing the second or third left-turn lane when it is needed.</p>

Table 4: Summary of the Survey of State DOTs for Phasing of Multiple Left-Turn Lanes

State DOT's	Q 2. Under what conditions does your agency allow permissive phasing at dual and triple left-turns?
Arkansas	Under no conditions
California	Caltrans
Colorado	No
Connecticut	Permissive phasing is not allowed for dual left-turn lanes. Protected only phasing is used.
Delaware	Typically, we do not
Iowa	We do not allow permissive phasing in these situations.
Kansas	I would never allow permissive phasing with a double or triple.
Louisiana	No Answer
Maine	Never
Maryland	We have none
Montana	<p>This agency does not introduce permissive signal phasing into the operation of dual or triple left-turn lanes. We only allow it at one location in the state to permissive and on only approach. There are no left-turns on the opposite approach. It was not a decision made by existing staff and it is only being allowed to continue permissive because its circumstance has recorded any accident trend or public complaint. This is a unique site.</p> <p>Since it is in operation with out demonstrated problems, we have taken the stances that “if it is not broken don’t rush to fix it”. It would be difficult to recreate these same instances.</p>
North Dakota	Do not allow
Nevada	Never. We do not allow permissive phasing on dual or triple left-turn lanes.
Oregon	Never.
Rhode Island	We do not allow permissive with the use of dual left-turn lanes.
South Carolina	None.
Texas	Operation of traffic signals is dependent on the responsible engineer’s judgment, however in practice; TX DOT does not operate permissive phasing at dual or triple left-turn lanes. Additionally, opposing left-turns are not usually allowed to operate at the same time.
Washington	Not applicable
Wisconsin	Protected only left-turn phasing is used at multiple left-turn lane intersections.

Table 5: Summary of the Survey of State DOTs for Phasing of Multiple Left-Turn Lanes

State DOT's	<i>Q 3.</i> Under what conditions does your agency allow protected + Permitted phasing at dual and triple left-turn lanes?
Arkansas	Under no conditions
California	None
Colorado	Double left-turns are used extensively with both protected (exclusive) and protected + Permitted signal phasing
Connecticut	None
Delaware	Typically we don't
Iowa	We do not allow protected + Permitted in these situations
Kansas	Again, never, with dual it should always be protected only for safety reasons
Maine	1. Never 2. Maine DOT policy does not allow protected + Permitted dual left-turns
Maryland	1. where forced to for lack of L/T storage 2. where we want less restrictive control during certain times
Montana	Does not allow
North Dakota	Do not allow
Nevada	Never
Oregon	Never
Rhode Island	We only use protected
South Carolina	None
Texas	Same as permissive phasing, in practice, TX DOT does not operate intersections with dual left-turn lanes with permissive / protected
Washington	N/A
Wisconsin	Don't use

Table 6: Summary of the Survey of State DOTs for Reducing the Number of Receiving Lanes

State DOT's	<p><i>Q 4.</i> At what distance of downstream of an intersection with dual or triple left turn lanes, does your agency allow a reduction in the number of receiving lanes?</p>
Arkansas	This is determined by capacity analysis and geometric restraints
California	(No answer)
Colorado	(No answer)
Connecticut	In addition to engineering judgment, guidelines for the extension of additional through lanes are referenced for left turn lanes as shown on the attachment. The green interval for the left turn is also considered to allow enough time for vehicles to merge after the intersection.
Delaware	It is based on the geometric of the roadway.
Iowa	We do not have written guidance on the distance.
Kansas	We do not have criteria established for this. For lane widths, we try to meet ITE's guidelines for Urban Major Street Design Book.
Louisiana	The length needed downstream varies depending on driver destination and traffic distribution within the turning lanes and/or through lanes and is site specific.
Maryland	Reduction width x speed/2
Maine	12 x Green
Montana	We have not had much success where we have dropped through lanes in close proximity down stream of a traffic signal. We have tried 1000 ft. and it did not work well. We have identified poor outside lane utilization and significant conflict at the merge. It is our position that to implement a multilane left turn the fundamental number to through lanes on the receiving roadway must equal the number of lanes serving the turning movement with out the existence of a downstream lane drop.
North Dakota	AASHTO and HCM guidelines
Nevada	We use the MUTCD and AASHTO Green Book guidelines for the distance needed.
Oregon	ODOT takes in consideration volume, speed and proximity of other intersections. We then plug into a SYNCHRO model to see if the rest of it works.
Rhode Island	We do not have any set criteria. Usually, if dual left turn lanes are used, the roadway has two travel lanes.
South Carolina	Our preference is to carry the lane for 1000 ft. and then develop the transition.
Texas	Again, this would be a decision based on engineering judgment and the requirements of the TxMUTCD.
Washington	A two-lane exit is required for the two-lane left-turn movements. In addition, this two-lane exit must extend well beyond the intersection. At a posted speed of 45 mph or higher, the minimum length is 1500 ft. At posted speeds, less than 45 mph the minimum length should be sufficient so that the advanced lane reduction warning sign will be placed not less than 100 ft beyond the intersection area.
Wisconsin	Typically, when we implement multiple left turns there are as many travel lanes on the receiving approach, as there are turn lanes. I can think of one situation where that is not the case-where there is lane drop on the receiving approach. At that location we drop the outside (Right) lane about 750 ft. (Does not include taper) from the intersection. That will change in <2 years when an improvement project will extend the four-lane section further from the intersection and the dual left condition. The reason for extending the four-lane section is to remedy operational issues at an adjacent intersection.